DISCRETE EVENT SIMULATION OF A SUPPRESSION OF ENEMY AIR DEFENSES (SEAD) MISSION

THESIS

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Abstract

Contemporary military campaigns increasingly count on the use of air power. Suppression of enemy air defenses (SEAD) operations have been a crucial element of military air power for 50 years. Several developments and evolution in both air defense and attack systems suggest that SEAD missions will continue to have growing importance to air forces. Since SEAD operations have a significant impact on air campaigns, it is important to examine their efficiency and identify improvement opportunities. This study explores factors that influence SEAD operations through use of a discrete event simulation built in Arena and subsequent statistical analysis of the results.

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Ahmet Aydın Çandır

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A/A	air to air
A/G	air to ground
AAA	anti-aircraft artillery
AGL	above ground level
AGM	air to ground missile
ARM	anti-radiation missile
ATO	air tasking order
ACSL	Advanced Continuous Simulation Language
AFSAT	Air Force Standard Analysis Toolkit
ANOVA	Analysis of Variance
β	half-width variation in percentage
C4	command, control, communications, and computer
CI	confidence interval
CRN	common random numbers
DES	discrete event simulation

DIS	Distributed Interactive Simulation
DoD	Department of Defense
DOE	Design of Experiments
DEAD	destruction of enemy air defenses
DARPA	Defense Advanced Research Project Agency
EW	electronic warfare
ECM	electronic counter measures
EOB	electronic order of battle
EADSIM	Extended Air Defense Simulation
FEBA	forward edge of battle area
GCI	ground control intercept
GUI	Graphical User Interface
HFR	harm failure rate
HARM	high speed anti-radiation missile
i	iterative increase in the number of replications
IA	information attack

IADS	integrated air defense system
MOE	measures of effectiveness
n_a^*	number of additional replications
NTG	number of targets
NATO	North Atlantic Treaty Organization
OR	Operations Research
OS	overall success
OCA	offensive counter air
Pk	probability of kill
R	range of the sensor
ROE	rules of engagement
Radar	radio detecting and ranging
S	variance with the present replication
SA	surface to air
SAM	surface to air missile
SLO	skill level of SAM operators

SOR	SAM on-air rate
SEAD	suppression of enemy air defenses
SEAS	System Effectiveness Analysis Simulation
SPINS	special instructions
SIMNET	Simulator Network
t	time, TOT
t_0	initial time
t_d	time detection
t_e	time exit
TOT	time over target
US	United States
UAV	unmanned aerial vehicle
v	velocity vector
v_{ag}	velocity vector of A/G aircraft
V&V	verification and validation
VV&A	verification, validation and accreditation

x_0	initial position
x_{ag}	initial position of A/G aircraft
x_{tgt}	initial position of target

DISCRETE EVENT SIMULATION OF A SUPPRESSION OF ENEMY AIR DEFENSES (SEAD) MISSION

I. Introduction

1.1 Background

Since the first use of aircraft in combat, the ways to defend forces on the ground has been a great challenge to the armed forces. There are reports of balloon and anti-balloon artillery in the American Civil War and the Franco-Prussian War, and in 1890 the Russians tested a field-gun battery against a balloon moored three kilometers away. The first airplane downed in combat fell to ground fire in the Italo-Turkish War of 1912; so when World War I began, there were precedents for ground-based air defense (Werrell, 1988: 1).

Small arms and artilleries were used to hit the aircraft during World War I. On the other side to make air defenses inoperative, aircraft could have made only strafing and bombing operations. Since that time, the activities of neutralizing, destroying, or temporarily degrading enemy air defenses has been known as suppression of enemy air defenses (SEAD) which led to the design and construction of aircraft systems and weapons for that purpose. Over the years, both attacking aircraft and air defense systems have evolved. German forces densely used anti-aircraft artilleries (AAA) during WWII. The Allies tried several ways to neutralize the German AAA, but the most effective solution was avoidance. With the advent of radio detecting and ranging (radar)

equipment, ground-based air defenses became more effective and more lethal. Towards the end of WWII, Germany attempted to develop a surface-to-air missile (SAM), but the technology necessary to provide guidance for a SAM was not mature enough (Neufeld, 1995: 152). Therefore, AAA continued to be the primary threat and avoiding AAA continued to be the primary tactic throughout the Korean War. Especially in the Vietnam War, the Soviet-built radar guided SA-2 SAM added a significant lethal dimension to air defense. Total combat losses due to ground-based air defense systems and the growing rate of attrition provided clear evidence that SEAD missions were highly important for maintaining aircraft survivability and led to an increase in the number of planned SEAD sorties. This resulted in the development of new SEAD missions and tactics against the evolving threat. Crucial steps in the evolution of the SEAD mission to actively jam enemy air defense systems included introduction of the EB-66 electronic warfare (EW) aircraft and employment of the first Wild Weasel SEAD aircraft, the F-100F carrying the AGM-45A Shrike anti-radiation missile (ARM).

Afterwards SEAD missions took an important role in Arab-Israeli Wars. In contrast to Vietnam's single threat, Israelis fought against an air defense umbrella consisting of a variety of systems, many with the ability to minimize the effects of electronic counter measures (ECM) such as jamming. In 1982, two important steps in the evolution of air defense and SEAD mission were demonstrated during the Bekaa Valley conflict between Israel and Syria. The Syrians constructed a complicated integrated air defense system (IADS). SAM and AAA sites were placed to build a forceful defense wall against attacks. In response, the Israelis developed a new tactic in the SEAD mission.

They used a combination of drones and aircrafts. Drones were flown as decoys to make SAM radars active and then SEAD aircrafts were used to employ standoff weapons.

The next major application of the SEAD mission was the Gulf War. As opposed to Syrian air defenses in 1982, Iraq had gathered an impressive amount of sophisticated equipment for their IADS, including both Soviet and European systems. It consisted of several thousand radars, approximately 10,000 pieces of AAA, up to 17,000 SAMs, and the seventh largest air force in the world (Brungess, 1994: 38). The major concern was to destroy or disrupt command and control centers, communication and electrical facilities of the Iraqi IADS instead of directly attacking the SAM sites. The SEAD packages were formed of F-4G high-speed anti-radiation missile (HARM) shooters, EA-6B electronic jammers, and a large number of drones to support other air strikes. The air campaign resulted in a disintegrated Iraqi IADS in the first two days by destroying or making inoperative many of the radars and SAM sites.

The last major example of SEAD operations was one of the most challenging of SEAD missions. In Kosovo, Serbians performed new tactics that they learned from Iraqi's experience. Instead of continuously operating their systems, they chose to change the locations of their mobile SAMs continuously and activate them intermittently. That fact protected their SAMs from exposure to NATO attacks. It also gave Serbian SAMs the chance to launch surprise attacks on the Allied Forces aircraft, resulting in the loss of an F-117 and F-16. This was resulted in that although strike aircraft were not always threatened, there was a requirement for a full complement of NATO SEAD assets airborne to support every strike package (Lum, 1999: 38).

Since the first use of aircraft in combat and the first response given from the ground, it was obvious that the fight between aircraft and air defense would continue for a long time. This is evident today with the continuing development of new weapons and improved tactics. Going forward into the 21st century SEAD missions will continue to mature with specialized aircraft to execute these important parts of the air campaign.

1.2 Research Problem

Contemporary military campaigns increasingly count on the use of air power. SEAD operations have been a crucial element of military air campaigns for 50 years. Several developments and evolution in both air defense and attack systems suggest that SEAD missions will continue to have growing importance to air forces. Twenty to thirty percent of all combat sorties in the recent three major conflicts were devoted to SEAD missions (Bolkcom, 2005: 5). Since SEAD operations have a significant impact on air campaigns, it is a necessity to determine their efficiency and improvement opportunities.

1.3 Research Objective

This study describes a method for modeling SEAD air combat operations in a discrete event simulation environment. The objective of this research is to present a flexible and responsive model by using discrete-event simulation to investigate the means of neutralizing, degrading, jamming or destroying ground-based air defense systems. Researching the efficiency of missions and commenting on the results for different scenarios are additional objectives of this study.

1.4 Thesis Organization

This thesis is organized in five chapters. Chapter two reviews simulation literature, combat modeling, and previous studies on related subjects. Chapter three defines the structure of the model, how it is built in Arena®, and gives some detailed information of the model. In chapter four, model results and conclusions are presented. The last chapter pulls together highlights from all chapters and makes some conclusions and recommendations for future research.

II. Literature Review

2.1 Systems and Models

A system is defined to be a collection of entities or components that interact with each other and with the environment in an attempt to achieve some goal (Hartman, 1985). Military systems fall into this defined category. The entities or components of the military systems might be aircraft, weapons, troops, or various sized units such as squadrons or battalions.

Systems can be categorized in two types, discrete and continuous. A discrete system is one for which the state variables change instantaneously at separated points in time. A continuous system is one for which the state variables change continuously with respect to time (Law, 2007: 70). If an aircraft is taken into consideration, it moves through the air in continuous time, but it can be modeled using a discrete event model to gain the convenience of computer programming and efficiency of computer operation (Hartman, 1985). Only a few systems are totally discrete or continuous but can typically be modeled as either to achieve the objectives of the study.

We often usually study complex systems to discover the characteristics of how they operate. A common objective in these studies is to analyze the behavior of the systems when different conditions or inputs are applied. With these studies we can gain information about the internal processes and relationships between the components of the systems. Thus we can make some predictions about the performance of the systems under new and untested conditions. Figure 1 (Law, 2007: 4) shows different ways in which a

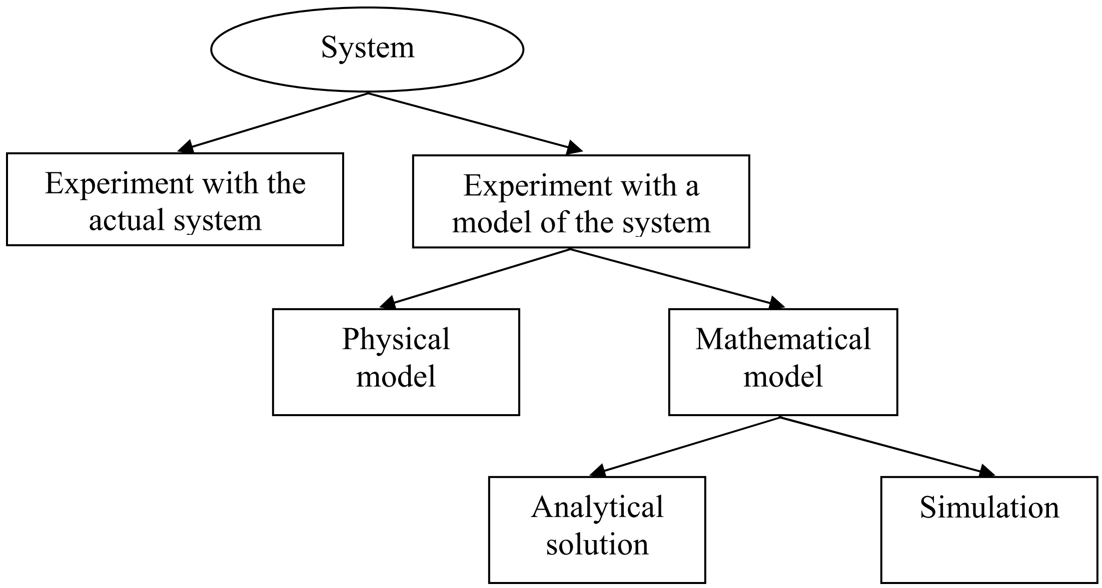

Figure 1. Ways to study a system (Law, 2007: 4)

system might be studied. Our discussion focuses on cases where we cannot experiment with the actual system. If it is possible and cost-effective to build a physical model of the system this can be the best way to get valid results for system performance under new conditions. For many systems such as military operations, it is not feasible to build a physical model of the system being studied. For these reasons, the behavior of military systems by means of mathematical modeling is studied.

A model of a real system is a representation of some of the components of the system and of some of their actions and interrelationships which is useful for describing or predicting the behavior of the system (within a reasonable range of inputs) (Hartman, 1985). When using a model, an important question to be answered is the validity of the model. Since no model can represent the real system perfectly, how closely it reflects the system and the accuracy of the outputs in regards to the model's purpose are the main issues for validity. Validity will be discussed in more detail later.

After deciding to construct a mathematical model of a system, the next step is to determine whether an analytical solution or simulation is more appropriate. If the model is simple enough, exact analytical solutions can be reached. But if an analytical solution to a mathematical model is not available or if such a solution requires a large amount of time and/or other resources, simulation emerges as the preferred method. Since most military systems are highly complex, it is generally impossible to model them using an analytical approach. Therefore, simulations are used in the analysis of military systems.

2.2 Combat Models and Their Classification

As defined before, a model is a simplified representation of some components of a system and some of their interactions which is useful in describing or predicting the behavior of the system. A combat model, usually a simulation model, is specialized to capture elements of military operations for investigative purposes or resources management purposes (Miller: Class handouts, OPER 671). It is useful and helpful to classify combat models for a better understanding. Although there are several ways to make this classification, Hartman's (1985) classification is used to classify them in this study.

Dynamic vs. Static

A static model represents a system at only a particular time, or represents a system where time has no effect. On the other hand, a dynamic model represents a system where time clearly plays a role. Monte Carlo models and a model of the lethality of a

single missile could be given as examples of static models. Most operational models and modeling of air combat are dynamic models.

Continuous vs. Discrete

In continuous models, state variables change continuously with respect to time. In discrete models, the state variables change instantaneously at separate points in time. In other words, the system can change at only a countable number of points in time. A discrete model can be used to model a continuous system. Many combat processes are continuous, but can be modeled using a discrete event model. The specific objectives of the study and the preference of the personnel programming the simulation are the main reasons in selecting a discrete model over a continuous model or vice versa. Although there are several examples of simulation software such as Simulink® and ACSL for building continuous models, the discrete-event simulation (DES) package Arena® as well as other commercial DES packages have continuous modeling capabilities as well.

Deterministic vs. Stochastic

If a model does not contain any probabilistic components or random effects, it is called deterministic. In a stochastic model, there is always some random input or process. If a missile is shot with the same parameters each time and it reaches the target in the same way, this model is deterministic. If the impact point is not known, then the accuracy of the missile might be modeled stochastically. A model can have both deterministic and stochastic inputs in different components to simulate both the certainty and randomness

of real life. If any portion of a system is modeled stochastically, the output of the model is also stochastic.

Descriptive vs. Prescriptive

A descriptive model describes how a system will operate if values for all of the input variables and decision rules are given by the model user (Hartman, 1985). Queueing models, inventory models and most combat simulation models are descriptive. A weaponeering program used to evaluate different munitions against a specific target to achieve the highest probability of kill (Pk) is an example of a descriptive model. A prescriptive model specifies how the system ought to operate to achieve some objective (Hartman, 1985). Prescriptive models are optimization problems with decision variables determined by solving the model for the given parameters of the problem. Linear programming, integer programming and network problem models are prescriptive models. A weaponeering program could also be used as a prescriptive model if you allow the model to select a weapon/target pairing given an objective function and constraints.

High Resolution vs. Aggregated

Combat models can also be classified by scope. Combat models are typically grouped using a multi-tiered or hierarchical family of models. This model hierarchy (Figure 2) is often displayed as a pyramid (Miller: Class handouts, OPER 671).

In this model hierarchy, combat models are placed at levels based on resolution and aggregation. Resolution is the degree of detail and precision used in the representation of real world aspects in a model or simulation (Department of Defense,

1995). A high resolution combat model (engineering level) is a combination of detailed interactions of individual combatants or weapon systems. The lowest level of the pyramid contains engineering levels of the detailed system representations. The next level presents the system as a combination of these detailed sub-units and includes the details of an engagement between a small number of platforms.

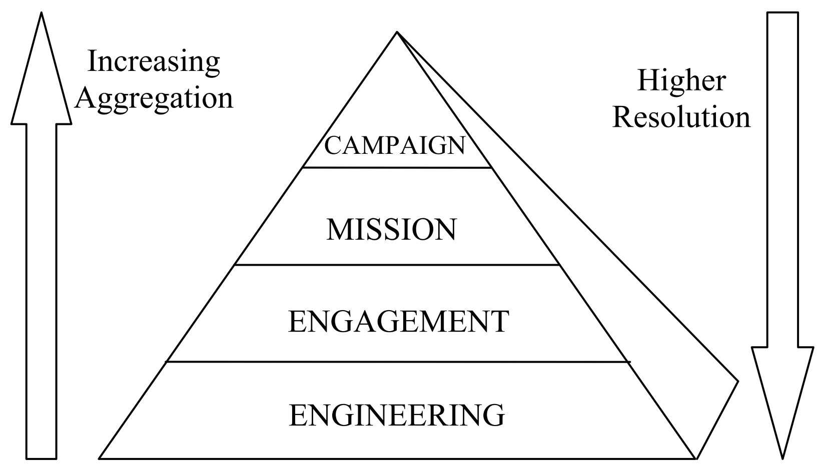

Figure 2. Combat Model Hierarchy

Above that, the mission level contains models where the systems begin to interact with a larger number of other systems. This level represents multiple-unit engagements or battles. These kinds of models give the operational performance of the systems. At the top of the pyramid, we find aggregated or low resolution combat models developed to model combat at the campaign level. An aggregated combat model is a model of larger units gathered from individual combatants with the loss of some detailed information. At this level, a major theatre war including joint and coalition forces over an extended period of time could be modeled.

At the bottom of the pyramid, high resolution models show the detailed representation of combat and represent small units. As we move up the pyramid, some

details are left out and the models become more abstract and entities begin to represent larger units. Similarly, as we move from bottom to the top of the pyramid the stochastic structure of high resolution models shifts into a more deterministic type of aggregated models.

Weapon versus passive target models are generally engineering level models to discover the accuracy and lethality of a weapon system against particular targets by emphasizing its hardware characteristics. One-on-one or few-on-few models are usually stochastic models between representing weapon systems in simplified engagement scenarios to represent the tradeoffs between the weapon systems. Combined arms task force models are generally stochastic and high resolution models that represent individual combatants and their detailed interactions at battalion level. The emphasis of these models is to determine the contribution of a particular system to overall force effectiveness. Mission specialty models represent a high resolution of a particular aspect or capability of a unit while considering the remaining capabilities of the same unit in less detail. Division level force models emphasize the force structure and the command and control functions of a division, since a division is the lowest level organization which has its own fire support and logistics. Campaign models have the largest number of participants including land, air, and naval combatants. The scenarios can last for months, thus deployment and logistics sides of war should be taken into consideration in these models. These models are highly aggregated and often deterministic with an emphasis on logistics, allocation and command and control of forces.

2.3 The Uses and Purposes of Combat Models

Combat models have a wide range of variety and uses. Today many countries' armed forces use combat modeling. Combat modeling as a tool for decision making can provide a more economic and effective means to evaluate alternatives and as an aid in determining appropriate force structures and capabilities. In addition, combat models can be used to educate staff officers and as a training aid in many different areas.

As the technology develops, new military weapon systems continue to improve and the cost of them continues to increase. While optimizing the design and maintaining the quality, reducing these costs is a principle area of concern for many countries. Combat modeling and simulation is one of the ways to approach this problem. New weapon systems and justifications are usually modeled by high resolution models. These models give a high level of description of the new systems using a variety of stochastic components. At the same time, they help in understanding the contribution of the system to mission effectiveness. These models may also be used to help evaluate new and modified tactics for the operators (Hartman, 1985). Different tactical developments can be tried and evaluated to find out the best or most effective under various conditions.

Combat models are also used to analyze the ability of different types of forces and major weapon systems for total force structuring. To understand the contribution of an existing unit or new weapon system, it can be modeled in a campaign level model. Such models can be used to evaluate unit size and composition to provide decision makers with a better idea about the structure and capability of the total force.

Another major area where combat models can be used is for training personnel. These models can contain military tasks to be evaluated and practiced by a specific staff. Models used for training often run in real time and allow for human interaction.

Distributed Interactive Simulation (DIS) is a simulation architecture used by the military for conducting real-time platform level war gaming across multiple host computers. It was first designed in support of the US Army Simulator Network (SIMNET) program for tank training by the sponsorship of the United States Defense Advanced Research Project Agency (DARPA) in the early 1990's. DIS consists of autonomous simulation entities such as battlefield, environment, and simulation support entities interacting in real time across networks. DIS transmits only the information for change in the state of entities across networks. It provides an open architecture where anyone can play. It is operable among different, virtual, live and constructive simulations. It facilitates development, training, mission planning and rehearsal.

As described above, different uses of combat models intend to achieve particular purposes. Military analysts frequently use models to evaluate future combat systems. For any combat modeling study there is always a tradeoff between time, cost and risk. Time may be the most limited resource in searching for the best answer for an ongoing combat operation or for training personnel in a specific task within a constrained environment. Cost-efficiency is a crucial concern in many Operations Research (OR) studies. Since military technology is the most expensive industrial area in the world, achieving the best capability at the lowest cost is a great challenge for the researchers and developers. The risk of being unsuccessful in combat clearly has a large impact on combat attrition. Combat models can be used to better understand what factors affect the level of risk and

how to reduce it. Although a model is not a perfect and exact representation of the real world, it can still provide insight on the relative merits of various courses of action for the decision maker.

Thus, the purposes of combat modeling can be summarized in two basic categories; analysis and training. Studies regarding development and effectiveness of weapon systems, force capability, and development of tactics, doctrine, strategy and policy are all common analysis areas. Another analysis area is operations support tools for helping to make decisions. In the training or education part, there are two main parts. One of them is the skills development for individuals or teams and the other is exercise drivers.

2.4 Model Verification, Validation and Accreditation

One of the most difficult concerns in modeling that developers or users of these models have to face is determining whether a model is an accurate representation of the actual system. This problem can be solved by the steps of verification, validation and accreditation (VV&A).

Model verification is the process of determining that a model implementation and its associated data accurately represent the developer's conceptual description and specifications (Department of Defense, 1995: A-8). Debugging the simulation computer program is a simple form of verification. In essence, verification seeks to ensure that the model is built right.

Model validation is the process of determining the degree to which a model and its associated data provide an accurate representation of the real world from the

perspective of the intended uses of the model (Department of Defense, 1995: A-8). In short, validation ensures that the right model was built. If a simulation is valid, then it can be used to make decisions about the system. An important point about model validity is that a valid model for one purpose may not be valid for another. Simulation models should always be built for specific purposes. Another important point about validation is that it is not a one time process undertaken at the end of model development, but an ongoing process conducted throughout model development.

Accreditation is a concept introduced by U.S. Department of Defense (DoD) in recent years. It is the official certification by a model user that a model, simulation, or federation of models and simulations and its associated data is acceptable for use for a specific purpose (Department of Defense, 1995: A-8). Accreditation assures that the model user takes responsibility for the decision to employ a model for a particular application and to make official conclusions based upon model results.

Credibility is also a related principle. If decision makers accept a simulation model and its results as correct and are willing to use the model results, that model can be deemed as credible. A credible model is not necessarily valid, and it might not be used as an aid in making decisions. In essence, credibility implies that the model provides believable results and is strongly influenced by model use by other organizations.

There are four basic approaches for deciding whether a simulation model is valid. Each of the approaches requires the model development team to conduct verification and validation (V&V) as part of the model development process (Sargent, 2005). In the first approach, which is frequently used, the model development team makes the V&V determination. Another approach leaves the V&V determination with the users of the

model. The third approach uses an outside team independent of both developers and users of the model to make the V&V decision. The last and rarely used approach incorporates a scoring model with subjective scores or weights for various aspects of the model and then accepts the model as valid if overall score meets or exceeds some passing score.

Some of the verification and validation techniques are presented here. Common verification techniques include writing and debugging a simulation program in subprograms, reviewing the program with more than one person, and running the model under several sets of input parameters and checking the results for reasonableness. One of the most powerful techniques that can be used to debug a discrete-event simulation program is a trace (Law, 2007: 249). In a trace, the states of the system are compared with hand calculations to check the operations of the program continue as intended.

Operational validation is determining whether the simulation model's output behavior has the accuracy required for the model's intended purpose over the domain of the model's intended applicability (Sargent, 2005). There are three basic approaches to make these comparisons. The first one is subjective using graphical comparisons such as histograms, box plots and scatter plots. Confidence intervals (CI) and hypothesis tests are the remaining two approaches that provide more reliable and objective results. Both confidence intervals and hypothesis tests can be used to compare means, variances, and distributions of the model outputs against the system outputs.

2.5 Previous Research

Many simulations involving air combat are modeled using special combat modeling software tools. These combat modeling tools are often produced for only US

release which means limited application. The software used in this study, Arena® is a discrete-event simulation (DES) package and has no restrictions for use by Non-US students. Our discussion focuses on some research about air defense and SEAD that does not use special purpose combat models.

Measuring the effectiveness of radar and infrared sensors in anti-air warfare area defense (Kulac, 1999) is an example of component-based DES developed in Java® using the Simkit simulation package. Analysis of ship self air defense system selection (Turan, 1999) is another Java® application using the Modkit simulation package.

A simulation analysis of a SEAD operation (Haugen, 1998) is another application of Simkit. Haugen conducted a study to evaluate the impact of intelligence delay on a SEAD operation. The results showed that the effectiveness of a SEAD operation is sensitive to information delay but the effective variable is the number of allocated SEAD aircraft.

Unmanned aerial vehicles (UAV) mission level simulation (Walston, 1999) is a DES study written in Java® using the Silk® simulation package. In that research, an object oriented simulation was developed to model the surveillance and active SEAD missions of UAVs. Analysis examined the effect of speed, endurance, and weather susceptibility on UAV operational effectiveness and the effects of radar cross section, threat density, and threat lethality on UAV SEAD mission performance.

Simulation analysis of UAV (Heath, 1999) is another DES example for an air platform. Analyzing mine avoidance tactics for autonomous underwater vehicles (Allen, 2004), dynamic allocation of weapons and sensors to ground targets (Havens, 2002), and waterfront force protection (Childs, 2002) are some other studies relating movement and

detection in DES. Simulation of autonomic logistics system sortie generation (Faas, 2003) and a DES model for reusable military launch vehicle prelaunch operations (Stiegelmeier, 2006) are some combat models built with Arena® .

III. Methodology

3.1 Introduction

This chapter describes the discrete event simulation model of a SEAD mission built for this research effort. It gives an overview of a simplified scenario which SEAD missions are tasked to attack an air defense system. The following sections contain model selection, model structure and description, and several assumptions made in the model.

3.2 Model Selection

The purpose of building a simulation model is to create a tool that produces necessary data for the researchers. Thus, selecting a model should be as simple as possible, but at the same time it should give a sufficient level of detail. The researcher has two options in this sense; one of them is to use an existing model and the other is to develop a new one. As mentioned in the previous chapter, there are not many examples where a researcher builds a combat model from scratch using discrete event simulation software. On the other hand, the Air Force Standard Analysis Toolkit (AFSAT) contains a number of legacy models designed to model combat at the engagement and mission level. One of these models is Extended Air Defense Simulation (EADSIM). This model is a mission level simulation used to assess effectiveness of many defense systems. It can be used to model a variety of scenarios including SEAD missions and other air defense operations. Another mission level model is System Effectiveness Analysis Simulation (SEAS) which helps to assess the impact of proposed systems in terms of high level

combat outcomes. However, these models have important disadvantages such as being very large and complex. Many of these combat modeling tools were produced with limited release outside of the US and is not necessarily available to international students.

The simulation model in this research was developed in the Arena® software package which is a commercial tool and available to all students. It is a discrete event simulation model designed for analyzing the performance of and the impact of changes on complex systems associated with supply chain, manufacturing, logistics, distribution and warehousing, and other areas. In the following sections, we present how a combat model was built in Arena® and the other details about a SEAD mission.

3.3 Model Description and Structure

Mission success is generally evaluated by two important measures in air to ground (A/G) employment. These two factors are target destruction and force survival. There are also several basic factors to be taken into consideration while planning A/G missions, such as enemy defenses, terrain, weather, target vulnerability, force requirements, navigation, and formations. There is no single approved solution to any tactical situation. Choosing reasonable, unpredictable tactics is the key in planning any A/G mission.

A/G missions can be created by flight packages with more than one flight or type of aircraft. Each flight must understand the mission objectives to be successful. There are two basic objectives for A/G missions. These objectives are target destruction and force survival where they influence flight planning through all phases of the mission. Factors considered during the mission planning process include mission objectives given in the air tasking order (ATO), rules of engagement (ROE) or special instructions (SPINS),

intelligence information, weather, terrain, weaponeering, navigation, communication, force requirements, and suppression of enemy air defenses (SEAD). If attackers are tasked to enter a threat ring or attack a threat site, they have to plan the mission with available SEAD assets. If there are no SEAD assets available to be tasked, an alternative way is tasking some of the allocated forces to the SEAD role. At this point, the vital role of SEAD missions and attacking a threat with or without SEAD assets can be noticed easily.

Offensive counter air (OCA) operations are aimed against essential targets of the enemy's air power. These targets include air defense control facilities; defensive missile complexes; command, control, communications, and computer (C4) facilities; airfield and supporting facilities; aircraft on the ground; and munitions and missile storage sites. OCA missions against air defense elements are called suppression of enemy air defenses (SEAD) which seeks to neutralize, destroy, or temporarily degrade enemy surface based air defenses by disruptive or destructive means. Disruptive SEAD involves a temporary disruption of enemy air defense assets. Employing a high speed anti-radiation missile (HARM), electronic warfare (EW), and information attack (IA) are the execution types of disruptive SEAD. EW involves the use of electromagnetic and directed energy to control the electromagnetic spectrum or to attack the enemy such as jamming or deception, and employment of anti-radiation weapons or weapons using electromagnetic energy. Destruction of enemy air defenses (DEAD) is one step beyond suppression and includes the physical destruction of enemy air defense assets through the use of conventional bombs and contemporary weapons such as cruise missiles. However, DEAD was not explicitly considered in this study.

Building a model is an art and requires a conscious effort. The modeler must make good decisions in selecting the right functional relationships, the best modeling techniques, the right scenarios, and the sources of inputs to get accurate results to aid the decision maker in forming conclusions about the system being modeled. Thus, the modeler should have knowledge of the simulation tool and an experience in the military operation to be modeled. After combining these factors, the modeler first takes steps to design the structure of a combat model. These include determining the purpose of the study, generating the appropriate combat scenario, defining the entities, their attributes (characteristics) and the events related to them. Once the model structure is defined, the modeler moves on to execution details such as battle initialization, specific processes to model (such as search, movement, and detection), battle termination, and required model outputs.

This structure gives an idea about the main processes of a combat model and how these processes are flowing in an existing model. A successful combat model scenario usually creates entities which perform the main processes: movement, searching, detecting and engaging. This provides the same logic and flow chart for each combatant side of the model (Figure 3).

A simplified SEAD mission was developed in Arena® for this research. This model is used to discover relationships and derive conclusions depending on input parameters. It is designed for analysis, with no objective concerning training. The model can't be interrupted or given different directions after execution begins. The current version of the model doesn't have a Graphical User Interface (GUI). As a result, all input parameters must be set directly in the code.

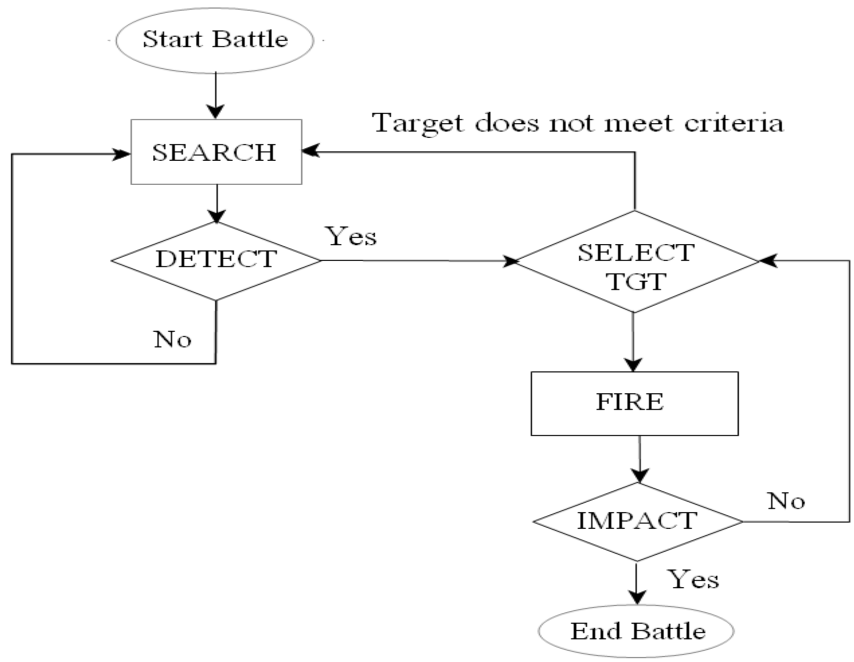

Figure 3. The Decision Making Flow Chart (Miller: Class handouts, OPER 671)

This model is dynamic and has an event stepped time mechanism. It represents both stochastic and deterministic features with its characteristics. While constructing the model, most of the effort was consumed to get a realistic as well as a flexible model. But building a more realistic model means the modeler must include more details. Thus, some assumptions were made to keep the model simple and responsive. These assumptions will be explained in the following section.

3.4 Model Assumptions and Details

When executing an air strike or an air-to-surface offensive counter air mission against specific targets in the battle area, the mission commander needs different types of aircraft and flights to compose a traditional package to ensure minimum attrition. SEAD and EW aircraft, air to air (A/A) and air to ground (A/G) flights are some typical

examples of a package. This model deals with only the units that carry and launch air to surface weapons for attackers and air defense units that carry and launch surface to air weapons for defenders.

A two-sided (Blue and Red) combat model was built for this research. The entities created for both Blue and Red are complete weapon systems that have some attributes and can move and interact with entities from the other side. The battle area is defined to be 100x100x5 miles and is represented in a x-y-z coordinate system. The geographic positions of both sides do not have an impact on the results of the battle with the Blue side located on the east side of the area and attack in the direction from east to west. Also there are no obstacles assumed to create any terrain factor. The battle time is determined as 10 days. There are three sorties flown each day and after each sortie both units are regenerated disregarding previous sortie attrition.

The main model consists of two major parts and an additional part to capture the outputs (Figure 4). In the first part, the Red SAM sites, the Red targets and the Blue A/G flights associated with these targets are created. HARMs, the search and attack patterns of both the Red air defense units and HARMs and the movement and attack phases of Blue A/G flights are built in the second part. The following paragraphs will go into detail about these two major parts.

In the first part, the entities are the units of air defense systems for the Red side. Basically, an air defense system has different categories of units. These include early warning, air surveillance, ground control intercept (GCI), SAM system acquisition, SAM system fire control, AAA fire control radars, engagement control stations, missile launch stations, and long, medium or short range SAMs according to the capability of the

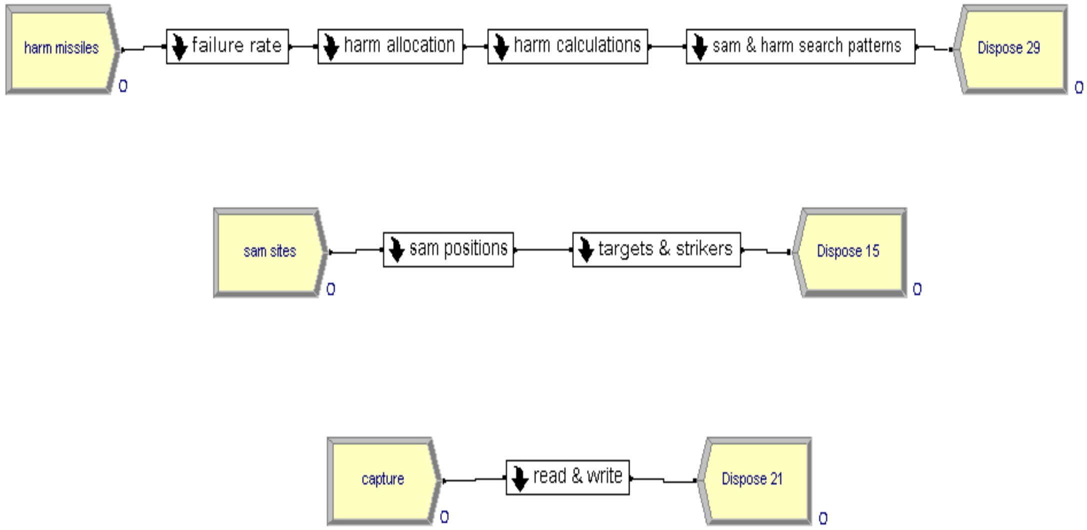

Figure 4. Main model

system. Since HARMs are anti-radiation missiles, the radars are the primary concerns and targets of SEAD flights. There are no particularly named air defense systems, weapons or aircrafts in this model. All of the players were intuitively created and given their important specifications only in numbers.

The Red air defense system is tasked to defend an area 100 x 100 miles with two SAM sites. This does not mean all the area should be covered by the defense umbrella. All air defense units are considered mobile, but they need to be stationary to operate. For each sortie, the defense systems are settled on a random location to defend two, four, or six strategic targets against SEAD and A/G flights (Figure 5). Those specific locations of the air defense systems were used as the main target positions for HARMs and missile launcher positions for A/G flights to avoid. The ranges of SAM sites are also determined randomly for each sortie. Although the ranges of two SAM sites are different from each other, the search patterns and the probabilities of detection and kill are the same.

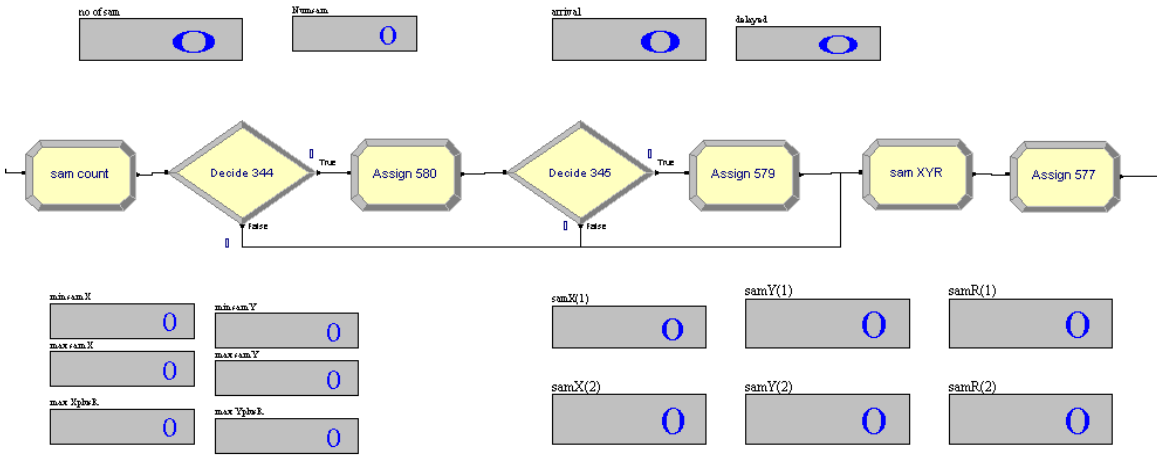

Figure 5. SAM Positions Submodel

After generating air defense systems and strategic targets, the Blue side attacking units and their initial positions were created according to the related targets (Figure 6). For each target, four Blue A/G attack aircraft are created. All targets are placed randomly in the range of the air defense system. This implies every A/G flight has to enter the area

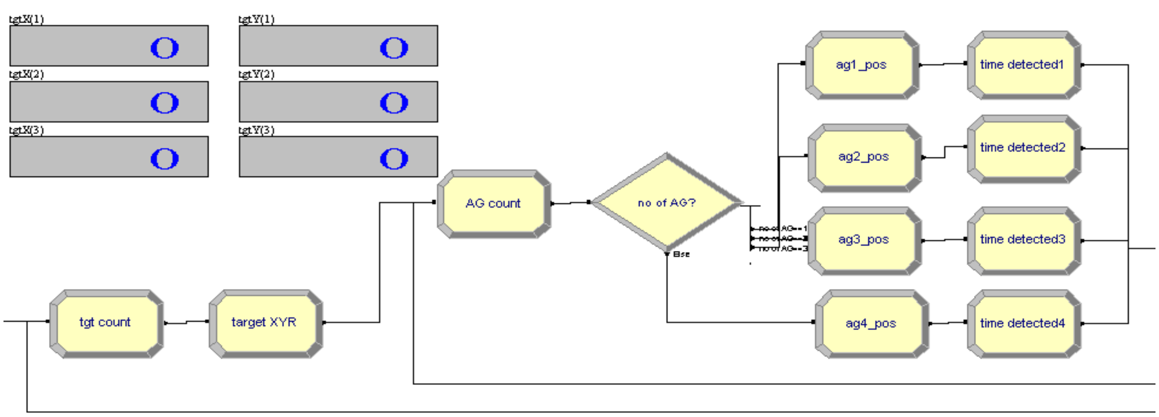

Figure 6. Targets and Strikers Submodel

in the range of the air defense system and become vulnerable to missiles of air defense systems. At the same time, Red air defense systems have to be exposed to Blue HARM missiles when they are trying to defend their strategic assets by operating their radars and attacking Blue A/G flights with their missiles. Thus a combat environment and attrition for both sides are created in the model.

In the same assignment modules, mathematical calculations are made for attackers (Figure 7). These are the calculations of vector velocities of attackers that help to move on to their assigned targets, calculations of times indicating when the attackers can reach to their targets, enter the threat zone and exit it. The A/G aircraft are assumed to fly at a constant velocity of 480 knots and execute a low altitude operation at 500 feet above ground level (AGL). A/G flights also fly in an offset box formation to make a time and altitude deconfliction between the elements. There is also some important information gathered for SEAD flights to help them generate a timeline for HARM launches in the second major part of the model.

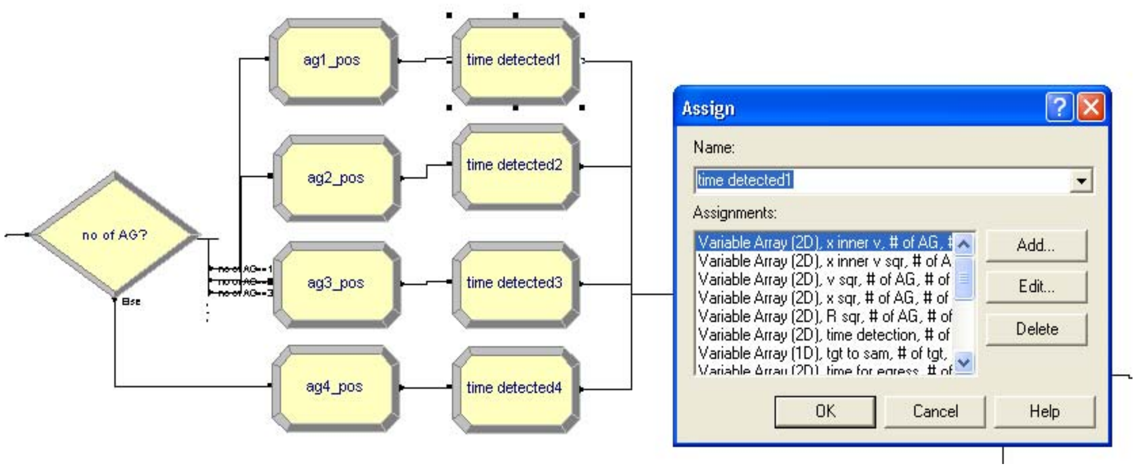

Figure 7. Calculation Assign Modules for A/G Aircraft

In the other part of the model, the entities are Blue HARMs that interact with the air defense systems of the Red side. These missiles are being launched from SEAD aircraft which are not modeled as separate entities. SEAD flight carries and launches eight missiles at each run. They usually do not enter the range of the threat and get exposed to the Red air defense missiles. They are assumed to form an imaginary box in the air which is called a SEAD box to provide deconfliction with the other Blue flights. SEAD aircraft are not involved with the battle directly, thus they are not vulnerable to the SAMs of the Red side.

After HARMs are created as entities for Blue side, there is a decide module to demonstrate the probability of some failures with HARM missiles or SEAD aircrafts. This module cancels some missiles by chance and shows the effect of an unplanned failure of missiles in the air during combat (Figure 8).

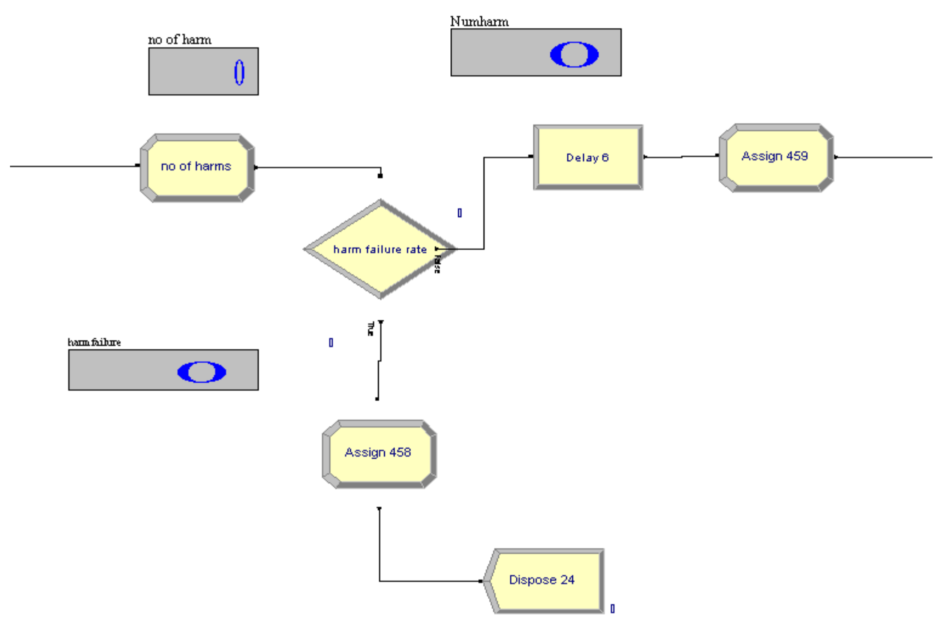

Figure 8. HARM Failure Rate Submodel

Afterwards, the allocation of HARMs to every SAM site is accomplished related to the A/G vulnerable times calculated in the first part of the model (Figure 9). Logic changes are associated with vulnerability times of attackers and make the distribution in three different ways. The eight HARMs are divided into 6 to 2, 5 to 3 and 4 to 4 missiles for each SAM site. This process also contains the calculations of time over targets (TOT) of each missile against Red SAM sites. HARMs are not launched reactively. The accuracy and flow of intelligence information and electronic order of battle (EOB) updates are assumed to be at a sufficient degree to make SEAD flights plan their shots prior to vulnerable times of A/G aircraft. Thus, all eight HARMs are already launched even if both SAM sites are hit by previous missiles.

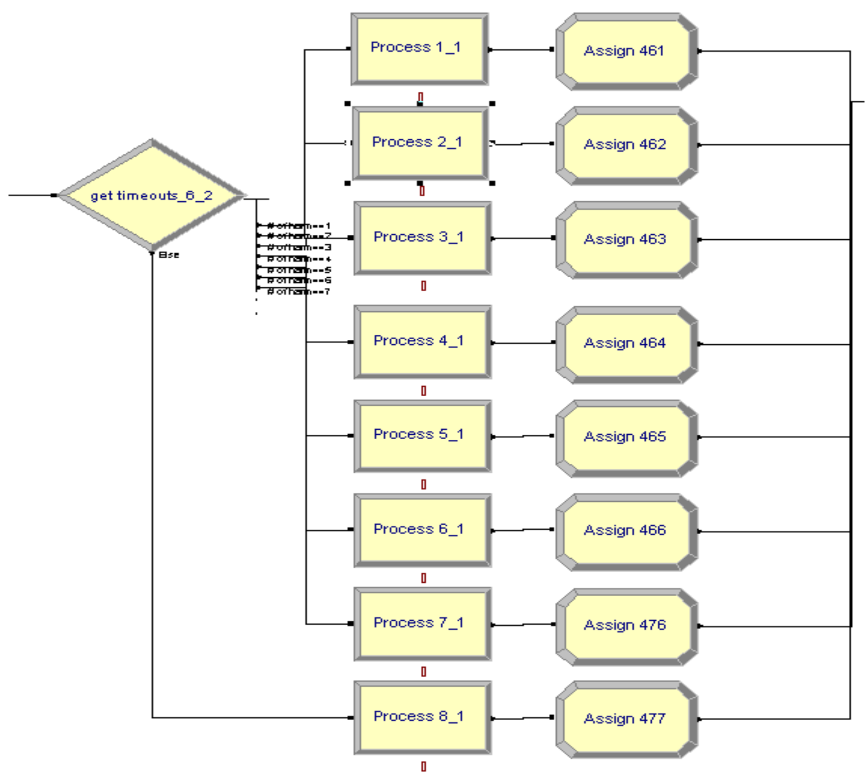

Figure 9. HARM Allocations Submodel

SEAD flight takes an initial launch position in the battle area according to the locations of the Red air defense units for the first HARM. After that they move to a new position in a calculated time which is related to the velocity of SEAD aircraft and the time between two consecutive HARM shots for the remaining shots. They remain in their SEAD box while they are making their orbits and preparing for new launches (Figure 10).

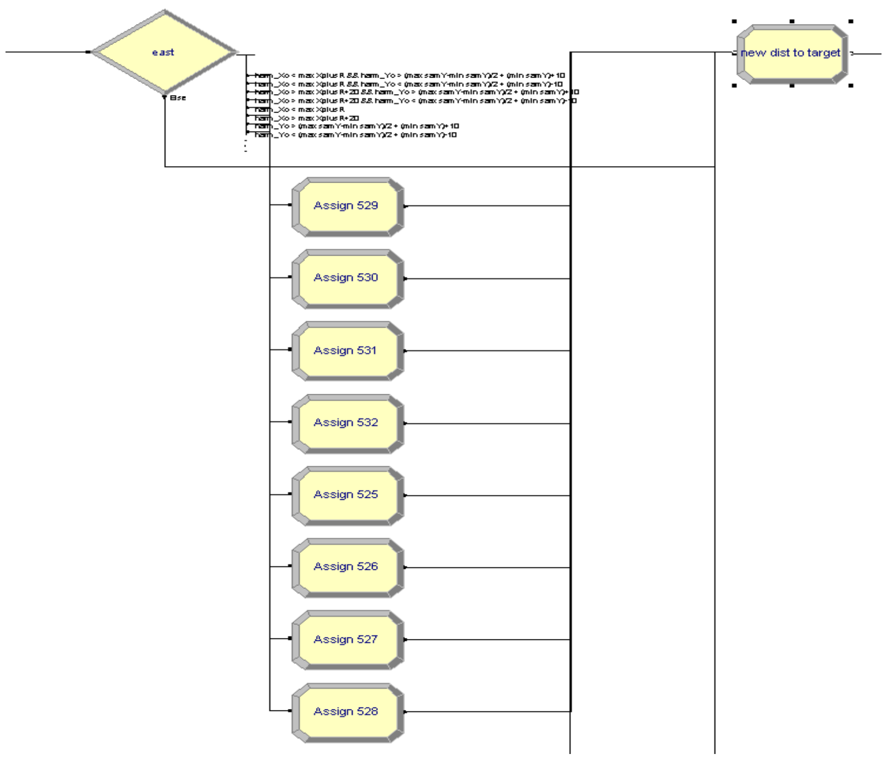

Figure 10. SEAD Box Submodel

SEAD flight determines the location of the SEAD box to bring the flight as near as possible to both SAM sites without entering Red missile ranges. There are two options to determine the location of the SEAD box. One is from the north and the other is from the east. There is logic to determine the placement of the box according to the locations and ranges of SAM sites to get the nearest and safe position (Figure 11).

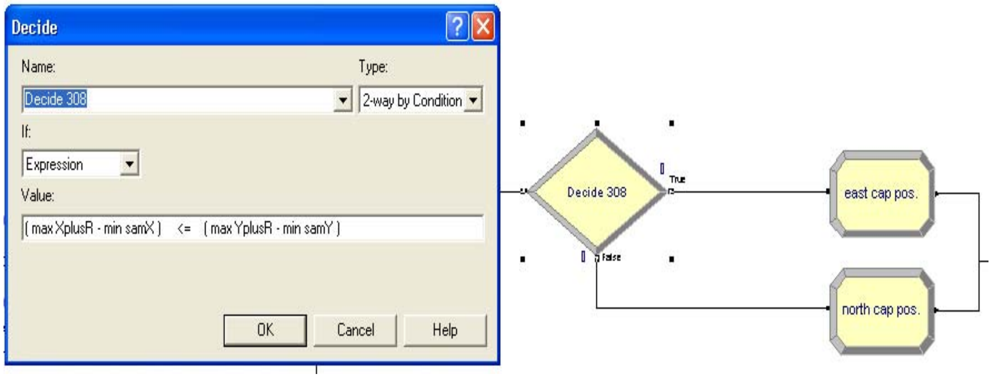

Figure 11. Logic of SEAD Box Location

After determining all the first locations of SAM sites, targets, A/G and SEAD flights and getting all the calculations related to time for A/G flight and HARM TOTs, the combat begins. The search and detection process of SAM sites continues from the first aircraft's entering time to threat area until the last aircraft's egress time (Figure 12).

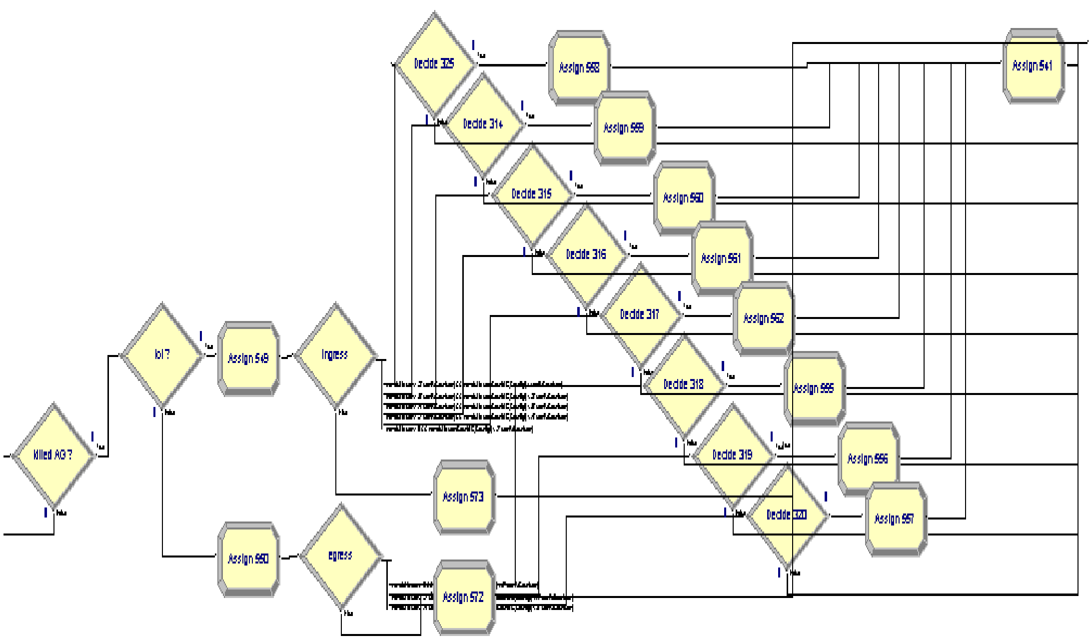

Figure 12. SAM & HARM Search Patterns Submodel

In this scenario, the air defense units are attacked by only SEAD aircraft carrying HARMs. Other types of military units playing a role in a SEAD mission are omitted. There are no other DEAD or A/G attacking assets carrying weapons to destroy air defense system units. EW assets only protect the SEAD flight and they are not assigned to destroy enemy air defense units.

The attackers were considered with their conventional or modern weapons against only Red A/G targets in the range of air defense units. SAM sites can only engage the attacking aircraft. Red air defense units cannot operate all the time because of the threat of HARMs. A stochastic detection model was developed for their operation. Their operational time is simulated by a triangular distribution. SAM sites are assumed to get a lock on only one target and launch one missile at a time. They can get different detection opportunities referred to as glimpses related to time intervals between search patterns. There is also another associated probability that varies in accordance with the skill level of SAM operators. For instance, a high level operator needs less time than a low level operator to detect and get a lock on the target.

After making detection, the operators launch a missile to hit the Blue attackers. They can engage just one target at each shot. The probability of detection depends on the distance and directions of the aircraft to the SAM sites. Once entering the threat area, the Blue attackers have a high probability of being hit by SAMs because they are moving toward the threat. The aircraft fly on a smooth surface and are not terrain masked. They are not assumed to make any defensive maneuver against SAM locks and launches which results in more attrition for the Blue side. On the other side, while executing the egress phase, their speed will be higher and they will show the aft of their aircraft which

decreases the probability of detection. Different values of probability of detection were applied to ingress and egress phases of the attack.

3.5 Movement and Detection in DES

Movement and detection are crucial issues that should be taken into consideration while building a combat model using a discrete event tool. Most of the time, both movement and detection have been done in time-stepped models. Time does not advance in regular intervals in discrete event simulation as the simulation time is moved to the time of next event. Although it seems hard and infeasible, there is a way to do both movement and detection in a discrete event approach (Buss and Sanchez, 2005).

In this research, there are SEAD flights and A/G attackers moving after the start of battle. They are assumed to fly at a constant speed of 480 knots and at a fixed altitude of 20,000 feet for SEAD aircraft and 500 feet for attackers. They have a linear two dimensional motion which is the simplest possible movement in a discrete event simulation.

Any aircraft starts its move at an initial position x_0 related to its assigned target at the beginning time of the battle t_0 with a constant velocity vector v. The velocity vector is computed related to the assigned targets of the aircraft to ensure they proceed to their targets. Storing initial position, time to start moving, and velocity vector of any moving entity are enough to determine the new location of the aircraft. The new location of any aircraft at time t will be computed by this equation of motion:

$$x_0 + (t - t_0)\vec{v} \qquad (1)$$

To find the TOT of an attacker, relative velocity is used. Since the target is stationary and its velocity is zero, the equation of motion relative to the target will give the TOT:

$$t = \frac{(x_{ag} - x_{tgt})}{\vec{v}_{ag}} \tag{2}$$

There is no need to store current locations of the aircraft at all times since they are not being detected every second of the simulation time. These computations are made only when a SAM site has an opportunity to detect and ask the location of the aircraft.

The cookie-cutter sensor is the simplest way of detection in a discrete event modeling, and is used in this study (Buss and Sanchez, 2005). Air defense units should not move while operating, that means the sensors of the SAM sites are stationary and each of A/G attacking aircrafts are the moving targets. Again at time t_0 the aircraft starts at point x_o and proceeds with velocity vector v to its target. It is important to note that position and velocity calculations are made relative to the sensor. The main concern is to find the detection time t_d at which the aircraft enters the sensor's range. The position of the aircraft at the time of detection is given by the following formula.

$$x_0 + t_d \vec{v} \tag{3}$$

The detection will occur when the distance between aircraft and sensor equals the range, R, of the sensor. Thus equation 3 becomes

$$\left\| x_0 + t\vec{v} \right\| \tag{4}$$

Then by completing the calculation of the length of this vector gives the solution to t_d

$$t = -\frac{x \cdot \vec{v}}{\|v\|^2} \pm \frac{\sqrt{\|v\|^2 (R^2 - \|x\|^2) + (x \cdot \vec{v})^2}}{\|v\|^2} \tag{5}$$

With the condition that the expression under the radical being non-negative, this equation will give two real and positive values for t. The smaller value is the answer for time detection t_d and the bigger one is for the egress time that aircraft exits the threat range t_e.

There is only one exception from the cookie-cutter logic in this model. After the aircraft come upon their targets and drop their weapons, they do not follow the same direction in the threat area to move on as seen in the Figure 13.

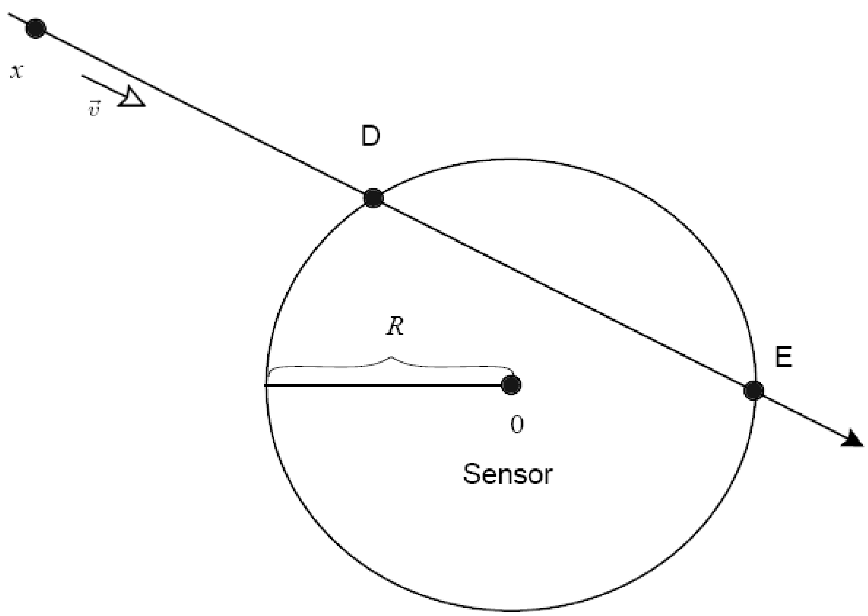

Figure 13. Cookie-Cutter Detection

To decrease the vulnerability and the chance to be detected by SAM sites, they use a different velocity vector named egress vector in the model to accomplish egress phase as soon as possible. They use the shortest path towards the safe area and minimize the total unprotected time in the threat zone.

The movement of A/G flights and their detection by SAM sites is briefly described here. The detection of SAM sites by HARMs follow the same cookie-cutter

logic. This time the entity in the sensor role, HARM, is moving, and the player in the target role, SAM sites, are stationary. HARM sensor begins to search the location of the SAMs at a calculated amount of time after launch. When the sensor of HARM receives any emission by the threats, it begins homing to the target. Once the homing is initiated, it flies a dive trajectory and arms its proximity fuse until it approaches the target and hits the target. HARM also has flexible logic and chooses the next highest priority target in its target list if it doesn't detect its primary target.

3.6 Conclusion

In this chapter, we defined an overview of a simplified scenario of a SEAD mission. We described the reasons for selecting the software, steps taken while building our model in a DES environment, a brief detail of the model structure, and the assumptions made to make the model reasonable. Results and analysis from our model are discussed in the next chapter.

IV. Results and Analysis

4.1 Introduction

The previous chapter defined the model built for this research. This chapter includes model results and analysis. In the first section, the factors and output data used in the model are introduced and determining the appropriate length and number of replications of the model to produce these output data is explained. The following sections include the design of experiments (DOE) and regression analysis of the main model, comparisons made between different competing systems on the basis of key performance measures, and the analysis of responses from the model.

4.2 Measures of Effectiveness

Various numbers of outputs could be obtained from a mission level simulation. The detailed model can easily give different performance measures from the results. In a combat environment, every unit has distinctive key measures to calculate their own performances. The performance values of each mission, number of attritions, number of ammunitions fired, number of targets detected, and number of targets destroyed are the most usual measures of effectiveness (MOE) in combat modeling. In this study, some of the outputs we captured are mission success for each mission, survivability score, overall success which is a combination of mission success values and survivability score, killed SAMs, detected A/G aircraft, killed A/G aircraft, killed targets, number of HARMs fired, total vulnerability time for A/G aircraft, total coverage time provided by SEAD flight.

Overall success (OS) is one of the most important MOEs considered in this research. As mentioned before, overall success is a calculated combination of the scores of each mission success and survivability. The mission success is calculated according to the number of targets killed by A/G strikers. The survivability score is another measure which gives the number of A/G strikers alive at the end of each sortie. Although the military commanders usually determine the weights of these measures related to the importance level of each one in the combat, the largest weight (75%) is given to mission success. These measures could practically be changed in the code when it's required.

The objective for half width variation for the mean of key MOEs is plus or minus 1%. The main model was run for 10 days and three sorties were accomplished for each day which gives us 30 sorties per one replication. The length of one replication was determined related to the duration of operational exercises such as Red Flag or Anatolian Eagle. First we ran the model for ten replications and captured an estimated variance to implement that value into the following equation. This formula assumes that as we increase the number of replications our estimate of the population variance will not change and we can reach an approximate expression for the total number of replications required to achieve a desired half-width.

$$n_a^{*}(\beta) = \min\left\{ i \geq n : t_{i-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{i}} \leq \beta \right\} \tag{6}$$

n_a^{*} is the number of additional replications needed to obtain a half width which is less than or equal to β which is equal to one in this study. $S^2(n)$ denotes the variance with the present replication number and i denotes the iterative increase in the number of

replications. The number of replications were iteratively increased and finally reached the value of 25.

4.3 Design of Experiments and Regression Analysis

After determining the number of replications and the replication length, the level of critical factors was determined that allow examination of the varying outputs. Four different main factors affected the outputs directly in the model. These factors are SAM on-air rate (SOR), HARM failure rate (HFR), skill level of SAM operators (SLO) in terms of seconds to react to A/G aircraft, and the number of A/G targets for each SAM site (NTG). These factors have two different levels for their low and high values. A 2^k factorial design is constructed to determine which factor has the greatest impact on the process and the key MOE OS. Arena®'s Process Analyzer is used to capture the necessary outputs. The main factors and their low and high values are shown in Table 1. Only NTG used a center level with a value of 4. A 3^1x2^3 factorial design was constructed (Table 2).

Table 1. Main Factors and Levels

Factors	Low	High
SOR	50%	100%
HFR	1%	25%
SLO	30 sec.	10 sec.
NTG	2	6

Table 2. Design Points

NTG	SOR	SLO	HFR
2	50%	10 sec.	1%
2	50%	10 sec.	25%
2	50%	30 sec.	1%
2	50%	30 sec.	25%
2	100%	10 sec.	1%
2	100%	10 sec.	25%
2	100%	30 sec.	1%
2	100%	30 sec.	25%
4	50%	10 sec.	1%
4	50%	10 sec.	25%
4	50%	30 sec.	1%
4	50%	30 sec.	25%
4	100%	10 sec.	1%
4	100%	10 sec.	25%
4	100%	30 sec.	1%
4	100%	30 sec.	25%
6	50%	10 sec.	1%
6	50%	10 sec.	25%
6	50%	30 sec.	1%
6	50%	30 sec.	25%
6	100%	10 sec.	1%
6	100%	10 sec.	25%
6	100%	30 sec.	1%
6	100%	30 sec.	25%

After 25 replications of the model for each 24 design points, key response variable OS values were collected. All these input and output variables are implemented in a multiple linear regression model to find out the relationship between these variables and the response variable. Multiple linear regression model attempts to find out this relationship by fitting a linear equation to observed data. This linear equation provides a regression line which describes how the mean response changes with explanatory variables. The observed values for response variable vary about their means and are assumed to have the same standard deviation. The fitted values estimate the parameters of

the population regression line. Since the observed values vary about their means, the multiple regression model includes residuals for this variation. The residuals are the deviations of the observed values from their means, which are assumed to be normally and independently distributed with a mean of zero and some constant variance. These assumptions are checked later.

By using Minitab statistical package, the stepwise regression technique is applied to determine which variables have a significant contribution to the multiple regression linear model. Four main factors in the model were applied first and had a very low predictive model. Interactions were added between these variables to obtain a more predictive model. Adding new variables to a regression equation will always increase our R^2 value, which gives the proportion of the variability in the response that is fitted by the model, even when the new variables have no predictive capability. However, the adjusted R^2 value corrects this difficulty. When new variables are added to the regression equation, the adjusted R^2 value does not increase, if the new variables have no additional predictive capability.

Other useful exploratory analysis tools for factorial experiments include main effects plots and interaction plots. Figure 14 shows the main effects plot for the response. This plot provides the information about how a factor contributes to the model without any interaction between the other factors.

The end points of the lines are the mean of response values at high or low levels of that factor's design points. The change in the mean of responses between levels of a factor is illustrated through the slopes of the lines. Usually slopes of the lines give the main idea of significance level of a factor on the response in these kinds of plots. A steep

increase between the means indicates that a factor has a significant effect on the response variable. A gradual change ends up with the conclusion of a minor effect on the response. HFR is as a good example of a gradual slope. HARM failure increases make little change in overall success. On the contrary, the other three factors show significant effects on the response with their steeper slopes. For NTG, increase in the number of targets gives a better result in the response. Although this increase generates new increases in the number of A/G aircraft and in the risk of attrition rate, it concludes a better score in overall success.

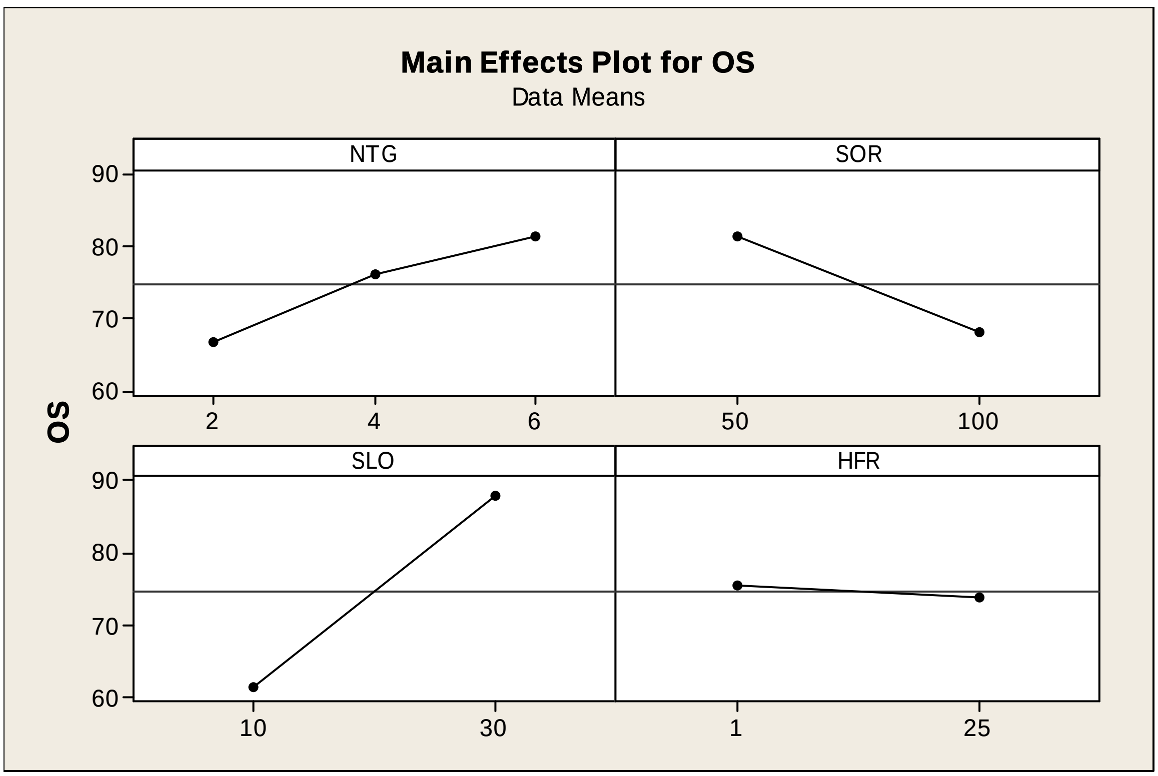

Figure 14. Main Effects Plot

On the other side, SOR another significant factor on the response introduces an interesting behavior. When the duration of on-air time of a SAM site increases, it will make a decrease in the response. Although the vulnerability of SAMs against HARMs

goes up, the response (overall success) drops off. Obviously SLO has the greatest effect on the response. As expected, the higher skill level makes a greater decrease in the response. On the contrary, lower skill level is almost completely unsuccessful.

Figure 15 shows the interactions between two factors among each other and the response. The different shaded lines stand for each level of the first factor among two factors examined. The end points of each line represent the two levels of the second factor. The values at those end points correspond to the response values depending on these two factors.

In the first subplot, we examined the NTG and SOR factors. There are three levels with three lines for NTG. The low and high levels of SOR are the end points of those lines. Their interaction between each factor determines the slope of that line and corresponding values on the right hand side represent the response variable OS. When

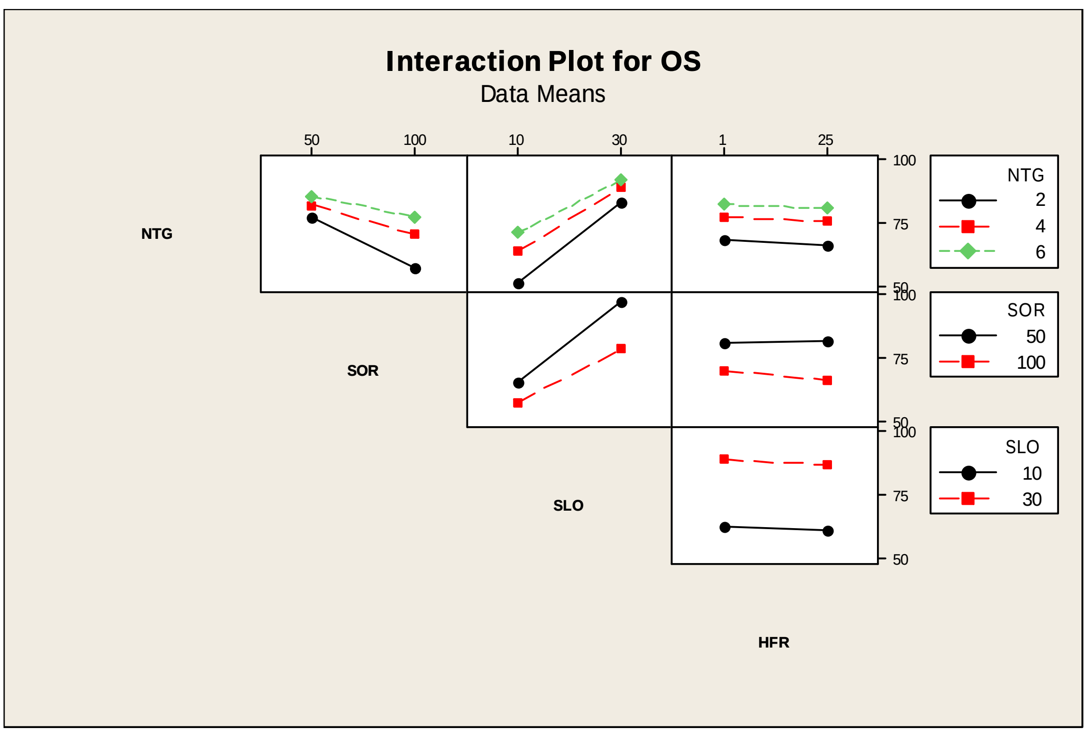

Figure 15. Interaction Plot for OS

NTG is at its low level which is the black line in this case, the high level of SOR is highly effective and make a great decrease in the response. When NTG level is increased, the same decrease in the response is observed as when higher levels of SOR are observed, but not as sharp slopes as seen in the first one. When SAM sites turn their systems on during the whole combat they can be more successful against the strikers, but their success is more evident with a low numbers of targets. When the number of targets increases, SAM sites cannot find enough time and chance to engage each target.

In the second subplot, we examined NTG and SLO factors interaction on the response. The value of 10 stands for the high-skilled SAM operators and 30 for low-skilled ones. High level operators have a great impact on the decrease of overall success. As expected, low level SLO can't be as successful as the high level. The same result as seen in the previous subplot provides the same conclusion. When the number of targets increases, the success for SAM sites will decrease. This provides the result of defending more than one target with one SAM site makes operators too busy to engage every target.

In the third subplot, NTG and HFR factors are analyzed. There is almost no slope for each line which means the HARM failure rate does not have a significant effect on the response. The only change among the three lines comes naturally from the NTG factor, as discussed the general impact of the change in the number of targets before. The same ineffectiveness can be observed from the other subplots of HFR on the third column. Independent of the other factors, HFR cannot make big differences in the response. In this case, being limited to only eight HARMs on each sortie and the failure rate values between the values of one and 25% do not make a crucial impact on the survivability of strikers.

The last interaction plot examined is the combination of SOR and SLO factors. The higher level in SLO will give the worse result in response again. Also the high level in SOR will make the same impact on the response by decreasing the percentage of overall success. This means despite the fact that being more vulnerable to HARMs, SAM sites could find more chances to detect and kill their targets.

The interaction between variables was also analyzed. Table 3 shows the correlation values.

Table 3. Correlation between the Variables

	NTG	SOR	SLO	HFR	SOR*SLO	SOR*HFR	SOR*NTG	NTG*SLO	NTG*HFR	SLO*HFR
NTG	1.00									
SOR	0.00	1.00								
SLO	0.00	0.00	1.00							
HFR	0.00	0.00	0.00	1.00						
SOR*SLO	0.00	0.53	0.80	0.00	1.00					
SOR*HFR	0.00	0.32	0.00	0.90	0.17	1.00				
SOR*NTG	0.75	0.61	0.00	0.00	0.33	0.20	1.00			
NTG*SLO	0.60	0.00	0.74	0.00	0.59	0.00	0.45	1.00		
NTG*HFR	0.38	0.00	0.00	0.86	0.00	0.77	0.28	0.23	1.00	
SLO*HFR	0.00	0.00	0.44	0.80	0.35	0.72	0.00	0.32	0.69	1.00

The correlation between “SOR*HFR” and “HFR” is 0.90. Since they are highly correlated, addition of the variable “SOR*HFR” may not significantly improve the model. The other variables were also examined in the same way. After fitting the regression line to this equation, it is important to investigate the residuals which are the differences between the observed and predicted values to determine whether or not they appear to fit the assumption of a normal distribution. Normality is one of the three basic assumptions of these residuals. A normal probability plot of the standardized residuals is

shown in the Figure 16. Despite two small light departures on both tails in the data, the residuals do not seem to deviate from a normal distribution in any systematic manner.

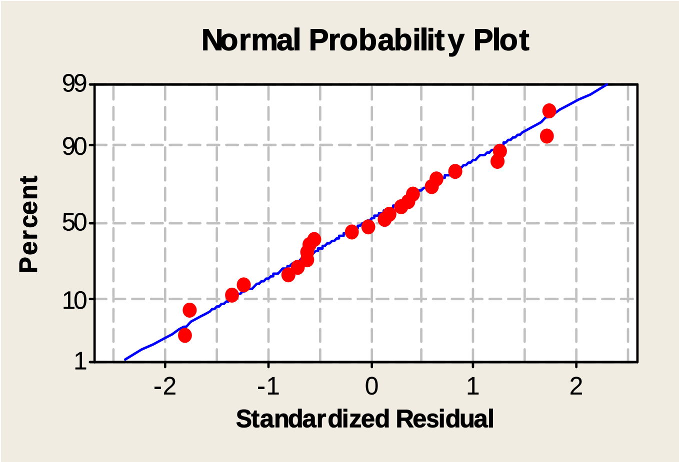

Figure 16. Normal Probability Plot of Residuals

Residuals can be thought of as elements of variation unexplained by the fitted model. Thus the other basic assumption about residuals is constant variance is checked by a scatter plot, the residuals against the fitted values (Figure 17).

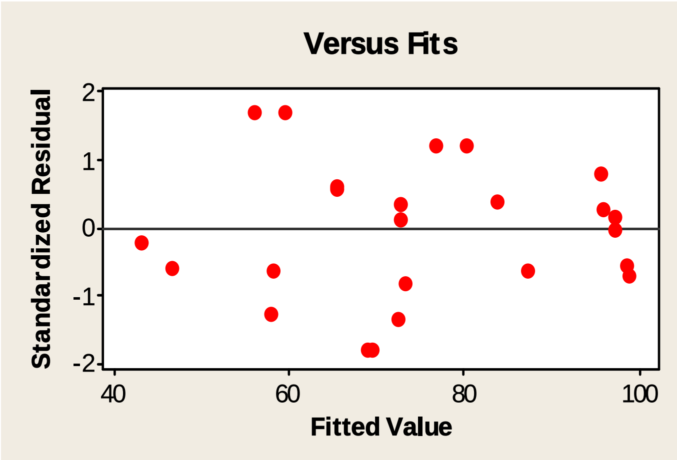

Figure 17. Residual plots vs. Fitted Values

Plotting residuals versus the value of a fitted response should produce a distribution of points scattered randomly about zero, regardless of the size of the fitted

value. If residual values increase as the size of the fitted value increases, the residual cloud becomes "funnel shaped" with the larger end toward larger fitted values which means the residuals have a non-constant variance. Although the residuals make a dense distribution between the values 60 and 100, a funnel shaped residual cloud is not observed. The scatter in the residuals between 60 and 80 is similar to the scatter in the residuals between 80 and 100. This suggests that the standard deviation of the residuals is roughly constant for the responses observed at each value.

After these steps, the regression model is reached. Minitab also provides a parameter table shown in Table 4 which helps to understand the variables that make a contribution to the model at different levels.

$$\begin{aligned} OS = 40.08 + 2.33NTG - 0.23SOR + 2.75SLO + 0.16HFR - 0.01SOR * SLO + \\ 0.06SOR * NTG - 0.15NTG * SLO \end{aligned} \tag{7}$$

Table 4. Parameter Estimates

Predictor	Coef. (β)	Std.Err.of Coef.	p-values
Intercept	40.082	4.143	0.000
NTG	2.3257	0.7864	0.010
SOR	-0.22849	0.04790	0.000
SLO	2.7469	0.1373	0.000
HFR	0.15828	0.09044	0.101
SOR*SLO	-0.011166	0.001373	0.000
SOR*NTG	0.056522	0.008407	0.000
NTG*SLO	-0.14742	0.02102	0.000

As seen on the first column, along with four main factors, three interaction variables also help to predict the response. The regression coefficients are shown in the second column. The third column contains the standard errors of the regression coefficients which can be used for hypothesis testing and constructing confidence

intervals. P-values or the significance levels for t statistics in the last column tell whether a variable has statistically significant predictive capability in the presence of the other variables. A p-value smaller than 0.05 means that variable is statistically significant in the model at the $\alpha = .05$ level. In some circumstances, a non-significant p-value might be used to determine whether to remove a variable from a model without significantly reducing the model's predictive capability. HFR has a non-significant p-value, however when it is removed, the model is less significant and the normality plot has larger deviations than the present one. These p-values should not be used to eliminate more than one variable at a time. A variable that does not have predictive capability in the presence of the other predictors may have predictive capability when some of those predictors are removed from the model.

Analysis of Variance (ANOVA) table (Table 5) explains the variability in the response variable. The amount of variability can be measured by the Total Sum of Squares. The ANOVA table partitions this variability into two parts. One portion is fitted by the regression model and labeled as Regression Sum of Squares. It's the reduction in uncertainty that occurs when the regression model is used to predict the responses. The remaining portion is the uncertainty that remains even after the model is used and labeled as Residual Error Sum of Squares. The model is considered to be statistically significant if it can account for a large amount of variability in the response.

Table 5. Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	p-value
Regression	8	6569.45	821.18	290.50	0.000
Residual Error	15	42.40	2.83		
Total	23	6611.85			

Mean Squares are the Sums of Squares divided by the corresponding degrees of freedom. The F Ratio is the test statistic used to decide whether the model as a whole has statistically significant predictive capability. The null hypothesis states that all regression coefficients are equal to zero. In other words the model has no predictive capability. The large values of F statistic provide evidence against null hypothesis and at least one of the coefficients is different from zero. The p-value for the F statistic is less than 0.001, providing strong evidence against the null hypothesis.

R^2 value is the squared multiple correlation coefficient and gives the proportion of the variability in the response that is fitted by the model. In this regard, if a model has a perfect predictability R^2 is equal to 1. The Summary of Fit shows these values in Table 6. As mentioned before the adjusted R^2 value makes a correction to the increase in R^2 value when new variables are added that have no additional predictive capability to the model. In this case, 99% of the variance in the response variable (OS) is explained by the model. The Root Mean Square Error is the square root of the Residual Mean Square. It is the standard deviation of the data about the regression line, rather than about the sample mean.

Table 6. Summary of Fit

R Square	0.994
R Square adjusted	0.990
Root Mean Square Error	1.683

4.4 Comparison of Different Systems

In this section, statistical analyses of the output from two different versions of the main model that might represent competing system designs is discussed.” The real utility

of simulation lies in comparing output of these alternative systems" (Law, 2007:548). In this sense, appropriate statistical methods are essential in making correct conclusions. Two options to construct confidence intervals for the difference between two performance measures are available. One is the two-sample-t approach which requires independence and equal variances but not equal sample size between two systems. However, equality of variances might not necessarily be a good assumption when simulating real world systems such as mission level combat systems. Thus a paired-t test is the other option. The advantage of this approach is it does not require equal variance and independence between systems. The sample sizes should be equal in this approach. Another consideration is using common random numbers (CRN) to achieve significant variance reduction (Law, 2007:555). The same random number streams and seeds is used for each system to synchronize our use of random numbers. Since this approach intentionally creates dependence between the systems as a variance reduction technique, it requires paired-t test approach to construct confidence intervals for the difference between two performance measures.

Two different systems are used in this study. In the first one, all A/G aircraft use the same exact time to be over their targets. However, it provides different times for strikers to cross the forward edge of the battle area (FEBA). In the other one, all strikers use same exact time to cross FEBA and this naturally provides different TOTs for A/G aircraft. The first system is named as System A, and the second one as System B. These systems are examined based on how these two different formations effect the vulnerability time of strikers in the range of SAM sites and the dispersion of HARM TOTs which are vital for strikers' survivability and our response variable OS.

First, how different TOTs and attack methods of these systems affect vulnerability time was examined. The same design points for both systems were chosen and a paired-t test between the means was performed.

In Table 7, the first line defines the design points. The letters stand for the system name, the numbers represent NTG, SOR, SLO, HFR factors in order. First the value of two for NTG was examined which means there are only two targets in the range. The other factors don't have any effect on vulnerability times. As seen on the first two

Table 7. Means of Vulnerability Times For Two Design Points of Each System

A-2-50-10-1	B-2-50-10-1	A-6-50-10-1	B-6-50-10-1
396.744	396.758	521.061	493.385
382.531	382.546	503.108	476.828
357.737	357.753	475.343	461.608
369.602	369.615	500.428	477.512
403.936	403.950	503.038	470.362
356.818	356.832	482.712	459.474
346.143	346.156	477.994	451.544
359.698	359.714	484.514	459.407
355.521	355.538	496.863	467.177
355.167	355.181	476.597	456.672
387.925	387.938	501.054	474.771
347.650	347.665	489.361	464.104
389.119	389.135	514.210	478.494
366.425	366.439	482.421	460.833
404.301	404.314	510.993	486.652
369.537	369.550	474.874	448.083
348.729	348.744	488.526	461.234
371.098	371.113	483.558	459.106
388.203	388.214	505.566	477.638
345.134	345.149	470.040	453.691
401.593	401.606	479.007	462.224
371.727	371.742	490.940	477.207
325.201	325.215	455.724	432.564
399.275	399.291	505.694	474.657
370.464	370.478	506.438	477.860

columns, the mean values are very close to each other. But the results of paired-t test (Table 8) which is equivalent to testing the null hypothesis $H_o: \mu_A - \mu_B = 0$, indicates rejection of the null hypothesis at the $\alpha = .05$ level. The confidence interval does not contain zero and the p-value is smaller than α value. Although vulnerability times of systems are statistically different from each other, the difference at the second decimal place in the vulnerability times relating to the systems is clearly not practically significant when there are only two targets in the range.

Table 8. Paired-t Test for Vulnerability Times (A-2-50-10-1, B-2-50-10-1)

	N	Mean	StDev	SE Mean
A-2-50-10-1	25	370.81	21.49	4.30
B-2-50-10-1	25	370.83	21.49	4.30
Difference	25	-0.014270	0.001394	0.000279
95% CI		(-0.014845, -0.013695)		
P-Value		0.000		

In the third and fourth column of Table 7, the mean values of vulnerability times for both systems at the value of six for NTG are shown along with results of the paired-t test (Table 9).

Table 9. Paired-t Test for Vulnerability Times (A-6-50-10-1, B-6-50-10-1)

	N	Mean	StDev	SE Mean
A-6-50-10-1	25	491.20	15.79	3.16
B-6-50-10-1	25	466.52	13.32	2.66
Difference	25	24.68	5.47	1.09
95% CI		(22.42, 26.94)		
P-Value		0.000		

The null hypothesis that these two vulnerability times are statistically same is rejected. But this time the confidence interval lies well above zero and is larger than the

first one. This result indicates that A/G aircraft in System A spend more time in the vulnerability area than A/G aircraft in System B. First it could be thought that all strikers in System A go into and out of SAM area at once and they have to spend less time in the target area. Since each A/G target location has a different distance to SAM site, and the vulnerability time window is calculated from the very first striker's entering time to the threat zone until the very last striker's exit time, it provides a dispersed and larger exposed time window for strikers.

Since the numbers of SAM sites and A/G targets are not big values such as two for SAMs and three for A/G targets for each SAM, and the maximum range of SAM sites is limited to 25, the difference between two means cannot be thought practically significant. But if these values are increased, the difference between means will get higher and begin to make things more difficult for attackers.

After finishing systems' effect on vulnerability time, the difference between the systems influences our key MOE overall success is discussed. Sixteen design points for each system are chosen. These points include the low and high values of four factors. By applying paired-t tests to these points, the following results were observed. Means and standard deviations of each system, 95% confidence intervals and p-values are listed in Table 10.

In the first two lines, the systems indicate that they are statistically different from each other since 95% CIs don't cover zero and the p-values are smaller than α. For both design points System B shows better performance than System A. The only difference between the two design points is HFR. HFR does not have a significant effect on OS. The ineffectiveness of HFR is discussed later.

Table 10. Paired-t Test for OS

Design Points		System A		System B			
no	NTG-SOR-SLO-HFR	mean	std dev	mean	std dev	95% CI	p-value
1	6-50-10-1	72.776	2.556	76.918	1.981	-5.001 , -3.281	0.000
2	6-50-10-25	73.176	2.385	74.939	2.346	-2.725 , -0.802	0.000
3	6-50-30-1	98.000	0.531	98.188	0.507	-0.468 , 0.092	0.177
4	6-50-30-25	97.898	0.544	97.748	0.581	-0.220 , 0.521	0.409
5	6-100-10-1	70.700	2.089	70.935	2.574	-1.546 , 1.076	0.714
6	6-100-10-25	66.521	3.122	69.554	2.791	-4.811 , -1.257	0.002
7	6-100-30-1	86.531	1.004	87.764	1.142	-1.672 , -0.795	0.000
8	6-100-30-25	84.225	1.173	86.178	1.186	-2.506 , -1.400	0.000
9	2-50-10-1	56.320	5.613	62.080	4.522	-7.688 , -3.832	0.000
10	2-50-10-25	57.218	5.111	60.963	4.784	-5.940 , -1.550	0.002
11	2-50-30-1	96.802	1.068	96.213	1.308	-0.108 , 1.285	0.094
12	2-50-30-25	96.255	1.318	96.027	1.296	-0.557 , 1.014	0.554
13	2-100-10-1	45.637	3.354	51.313	5.499	-8.260 , -3.100	0.000
14	2-100-10-25	42.547	2.653	49.113	4.720	-8.483 , -4.650	0.000
15	2-100-30-1	72.063	2.562	71.990	3.878	-1.653 , 1.800	0.930
16	2-100-30-25	67.257	3.900	68.935	3.779	-3.218 , -0.139	0.034

In the following two lines, a decrease in SLO from the first two lines is observed. A/G aircraft will be more successful when the skill levels of operators decrease. The rise in the mean values is an obvious proof of this development and these OS values are the highest ones among all these design points. At the same time, it cannot be said this change creates a difference between two systems as seen by. Failing to reject these systems are statistically different from each other for both design points at SLO value of 30 sec.

In the fifth and sixth lines, the SOR and SLO level is increased to their high values. In line five, no difference between two systems is observed but in line six the effect of HFR on OS is seen. By decreasing OS value from 70.7 to 66.5, HFR provides a

statistical difference between System A and System B. In this case, HFR acted as a key factor with the high levels of SOR and SLO on changing OS value.

In lines seven and eight, no statistical difference between competing systems is observed. The major reason for this result is the high level of SOR accompanying with low level of SLO. As mentioned before, the high level of SOR make an interesting decrease in OS although SAM sites spend more time exposed to the threat of HARMs.

The remaining lines in Table 9 are a repeat of the same factor levels in the top of the table with a change in NTG value. The number of targets in the combat area is decreased from six to two. In lines nine and ten, no statistical difference between two systems is noted. However, comparing the mean response values with lines one and two, there is a great decrease in OS values. It indicates that, when the number of targets decreases in the area, SAM operators find more chances to engage their targets. Thus, they can detect and kill more aircraft which results in lower values of OS.

In lines 11 and 12, the highest scores of OS are seen again after six target versions of these design points. It proves the same idea above about the effect of the number of targets on OS. The same results for the rest of the designs are observed. Here again, the results fail to reject the claim that these systems are statistically the same. In lines 13 and 14, better results with System B are shown and in lines 15 and 16, a significant effect of HFR on the results is observed. A high value for HFR shows System B is better in the last comparison.

The results and comments are discussed next. As opposed to our original expectations, System B showed better performance in most comparisons. Although the high values of SOR make an increase in exposed time to HARMs, the overall success

decreased. When the number of A/G targets and normally the number of A/G aircraft decrease in the range of SAM sites, SAMs killed more and gave a significant damage to Blue side. This shows the importance that EW assets should increase suppression with jamming to make SAM sites busy and inoperative. With few exceptions, HFR has no effect on the results. Since only eight HARMs are used in each sortie and the probability of failure rate cannot be too high, this result was no surprise. Finally the skill level of operators could be vital for both sides. When the value of SLO decreases, Blue side success increases. When SLO increases, Red inflicts greater damage to its opponent.

4.5 Conclusion

In this chapter, output analysis was discussed. First the appropriate length and number of replications of the model to produce necessary outputs was determined. The factors contributing to the model were then examined which resulted in a regression analysis with a factorial design. Finally the results of different competing systems were analyzed and conclusions about the factors in the model were drawn. Chapter 5 will discuss the highlights of this study.

V. Conclusion

5.1 Introduction

The previous four chapters presented the research that was undertaken. First a brief summary of SEAD mission evolution was introduced followed by a literature review on simulation, combat modeling and previous studies on related subjects. Next, important model details and information was provided. The last section analyzed the outputs of the model and provided conclusions. This chapter will give highlights from the previous chapters and make conclusions and recommendations for future research.

5.2 Summary of the Research

The objective of this research was to build a responsive and flexible model using a discrete event simulation to investigate the effectiveness of a simplified SEAD scenario with its different factors. Thus simulation cannot by itself be a perfect representation of real world, the plan was to build a mission level model with enough details to draw conclusions. First the important factors that should be included in the model to represent a SEAD mission were designed. Several assumptions were made to keep the model feasible and simple. After determining the entities and main states of the entities, model construction began.

Movement, detection and searching were the major challenges for a combat model in an event-stepped simulation. After developing the main model, minor changes were made to the model to mirror real-world situations. These models involved the

characteristics of our design points which were used in regression analysis. The models were run for 10 days with 25 replications. Outputs from these different models were captured. The most important measure of effectiveness which is OS was evaluated. The study concluded with analysis and comments of the results.

5.3 Conclusions of the Research

Four main factors were used in the model. These factors are SAM on-air rate (SOR), HARM failure rate (HFR), skill level of SAM operators (SLO) in terms of seconds to react to A/G aircraft and the number of A/G targets for each SAM site (NTG). The key MOE was determined as overall success (OS). Also two different systems were built to make comparisons. In System A, all A/G flights use only one TOT. In System B, A/G flights use different TOTs but same FEBA crossing time.

The results of the research show that when the exposure times of Red SAM sites against Blue HARMs increase, the higher levels of SOR always decrease Blue OS level. When NTG decreases, the success of Red SAM sites proportionally increases. It indicates that when the busy time of SAM operators and systems drops, they are more lethal against Blue forces. Naturally SLO provides results as expected and shows that skill level of operators significantly effects system performance. Finally HFR is the most ineffective factor in this research. Because of the low number of HARMs, HFR does not make major effects on the scores.

Another result is System A causes Blue A/G aircraft to spend more time in the range of Red SAM sites which increases the vulnerability time of System A over System B. Because of that reason, System B shows a higher Blue OS in most of the runs.

5.4 Recommendations for Future Study

The model can be enhanced by increasing the scope of this simulation. A simplified scenario of a SEAD mission was modeled. The number of SAM sites, targets, SEAD and A/G flight are limited. By increasing these numbers with minor logic changes in the model, more representative system performance could be captured. Model fidelity could be significantly increased by adding A/A, EW capabilities, intelligence and EOB update processes in support of these missions.

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Vita

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14. ABSTRACT

Contemporary military campaigns increasingly count on the use of air power. Suppression of enemy air defenses (SEAD) operations have been a crucial element of military air power for 50 years. Several developments and evolution in both air defense and attack systems suggest that SEAD missions will continue to have growing importance to air forces. Since SEAD operations have a significant impact on air campaigns, it is important to examine their efficiency and identify improvement opportunities. This study explores factors that influence SEAD operations through use of a discrete event simulation built in Arena and subsequent statistical analysis of the results.

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